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THESIS

A MANNING AND MAINTENANCE EFFECTIVENESS MODEL APPLIED TO THE COMMUNICATION DIVISION OF A "KNOX" CLASS DESTROYER ESCORT

by

Clifford Stephen Perrin

September 1975

Thesis Advisor: Donald P. Gaver

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A Manning and Maintenance Effectiveness Model
Applied to
the Communication Division
of a
"KNOX" Class Destroyer Escort

by

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Submitted in partial fulfillment of the
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ABSTRACT

The study objective was to investigate the problems of ship manning effectiveness, specifically in the maintenance and repair areas, using various probabilistic modeling and data analytical techniques of operations research. Maintenance and Material Management data from the Maintenance Data Collection System were used for estimating failure rates, repair rates and maintenance deferral rates for each type of equipment. These rates were then used as inputs to the mathematical models. The models could then predict system availability which depends on manning level and the rate of repairs deferred for various reasons.

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I. INTRODUCTION

This project was defined and was under the direction of Professor Donald P. Gaver, Department of Operations Research and Administrative Sciences, of the Naval Postgraduate School, in cooperation with Dr. S. Sorensen of the Naval Personnel Research and Development Center, and was sponsored by NPRDC. The study objective was to investigate the problems of ship manning effectiveness, specifically in the maintenance and repair areas, using various probabilistic modeling and data analytical techniques of operations research.

The author undertook a pilot study: to investigate the availability of key equipment in the Communcations Division of the Operations Department on a "KNOX" Class Destroyer Escort Ship.

Maintenance and Material Management data from the Maintenance Data Collection System (3-M/MDCS) were used for estimating failure rates, repair rates, and maintenance deferral rates. These rates were then used as inputs to the mathematical models from which equipment availability could be predicted, as the latter depends upon maintenance personnel available. Primary emphasis was placed on the analysis of the available relevant data, which could be easily manipulated to yield meaningful parameters as input into the model.

The Communications Division is a large system, itself consisting of many complex sub-systems which fail and need to be repaired. The entire ship, likewise, may be considered to consist of several systems, each contributing to the readiness and availability of the ship for combat; that is, the ability of the ship to maintain some Readiness Condition for an extended period of time.

Simplifying assumptions are made in order to reduce the size and complexity of the system: only those sub-systems judgementally deemed critical to maintaining mission capabilities necessary for combat are explicitly considered as failure-prone and in need of maintenance. A single carrier Task Group was selected to be the operating environment, and no other communication responsibilities are assumed to be placed upon the ship. One hundred percent availability of the associated equipment peripherals was assumed; that is, microphones, patch cords, antennae and various other items, having spares readily available and low failure rates.

II. NATURE OF THE PROBLEM

A ship at sea must be a self-maintaining entity in order to successfully perform an assigned mission. The proper manning levels could have a significant impact on whether or not a ship successfully completes the assigned mission. This impact could vary with (a) equipment repair times, the latter being related to the experience, ratings, and numbers of men aboard, (b) equipment failure rates, these depending on personnel skill and training, assuming that personnel with the proper Naval Enlisted Classification to do the work were on board. Equipment availability also (c) depends upon spares availability. Lack thereof influences the rate of deferrals.

Representing one component of mission success, equipment availability in the Communications Division and its effect on mission success was considered, using the criteria of the above paragraph. Manning levels and lists of equipments were then identified, by arbitrarily selecting a "KNOX" Class Destroyer Escort as a base case.

The USS DOWNES, DE 1070, was used as a prototypic situation from which to gather equipment loadings and authorized personnel manning levels. An Item Designation Report, Ref. 1., Ship Equipment Configuration Accounting System (SECAS) Report Number 502.1, was used to determine the

quantity and location of the equipments of interest. Manning levels for the areas of interest were determined by reviewing the appropriate BUREAU OF NAVAL PERSONNEL REPORT 1080-14. These equipment and personnel loading factors were used to provide a basis from which to initiate the model. Charges in equipment and personnel can be made in the model, so that (a) sensitivity studies may be made, and (b) the model may be applied to quite different shipboard environments.

The capabilities that were considered to be necessary for combat, and the critical sub-systems for each specific capability are identified by equipment name and Equipment Identification Code. These acronyms and names are defined in Appendix A. The Networks were as follows:

(1) Network Number 1, simplified to an uncovered UHF transceiver the AN/SRC-20 (EIC - QD3S).

(2) Network Number 2, simplified to consist of an uncovered UHF transceiver the AN/SRC-20 (EIC - QD3R).

(3) Network Number 3, simplified to consist of a UHF transceiver the AN/URC-9 (EIC - QD48).

(4) Network Number 4, simplified to be a UHF transceiver the AN/URC-9 (EIC - QD48).

(5) Network Number 5, simplified to be the (KY-8) and an UHF transceiver the AN/SRC-20 (EIC - QD3R).

(6) Network Number 6, simplified to be a KW-7 (EIC - QF1O) and a HF transmitter the AN/URT-23 (EIC - QE1N).

The teletypewriter and the HF receiver were not considered critical beceuse spare systems exist to take the load.

(7) Network Number 7, simplified to an UHF transceiver the AN/ SRC-21 (EIC - QD3S), KW-7 (EIC - QF1O).

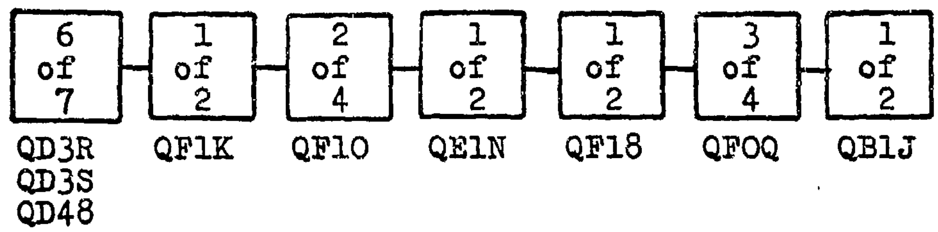
(8) Network Number 8, simplified to the KG-14 (EIC - QFOQ) and KW-37 (EIC - QF18) and a VLF/MF receiver the AN/WRR-3B (EIC - QB1J).

The above capabilities and equipments were selected for attention as a result of consultations with Naval Officers who had spent at least one tour on a "KNOX" Class Destroyer Escort Ship. These simplified specifications were considered general in nature and related to the Command and Control mission of this class of ships. The following block diagram illustrates a minimum path representation of those equipments that must operate in order for the system to function. The equipments comprising each block are listed below. Where more than one equipment is listed below a block, the equipments were considered interchangeable. Specifically in the first block, 6 of 7 means that at least 6 pieces of the 7 available equipments must function for the block to function, and the block must be operating in order to have the system operate. The failure of two pieces of equipment in block one would thus cause the system to fail by this definition, where in fact only one of the sub-systems has failed.

System failure by this definition is the loss of at least one sub-system.

Figure 1

Minimum Path Representation of System Availability



III. INVESTIGATION OF DATA

An investigation of the data supplied by Fleet Material Support Office was undertaken to determine whether meaningful repair rates and failure rates could be extracted for each type of equipment in the model. The data that were used in this analysis were from the complete 3-M/MDCS file from 1970 to July 1975, covering all ships reporting to the 3-M system, on the listed equipments. It became immediately apparent that the time in man-hours to repair any failed equipment was easily extracted from the data source. This was done for all the equipment. On the other hand, meaningful data on times between failures, leading to estimates of equipment failure rates were not as readily accessible; this difficulty will be addressed subsequently.

One of the initial objectives of this study was to relate manning levels to maintenance effectiveness, and thus to the reliability and availability of the equipment. The data concerning times to repair were further analyzed to extract the mean time to repair (MTTR) for each critical rating associated with the Communications Division; i.e., ETC, ET1, ETN2, ETN3, ETSN, ETR2, ETR3, RMC, RM1, RM2, RM3, RMSN. These twelve ratings which reflect the skill levels and pay grade of the repairmen were then merged

into eight rating groups for this analysis. The title given each group reflects the majority of the repair actions undertaken by members of that group. The titles and members are as follows:

ET1 - ETC, ET1
ETN2 - ETN2
ETN3 - ETN3, ETSN
ETR2 - ETR2
ETR3 - ETR3
RM1 - RMC, RM1
RM2 - RM2
RM3 - RM3, RMSN.

Individualized MTTR parameters were computed over all maintenance actions in terms of man-hours expended during the repair action for organizational level repair actions. Then data sorts of successively greater refinement were made in order to produce more specific information. For example, MTTR was computed for maintenance actions completed within one day of detection of failure, between two and four days, and for greater than five days after failure.

This study was directed toward the on-board maintenance actions that led to a completion of repair. For this reason, the author chose to utilize only the MDCS data cards MCE (Maintenance Closing Event) and CSMA (Completed Shipboard Maintenance Action). The CSMA record form is filled out by the organization actually performing the repair. It is used for organizational level or what is referred to as "normal repair" in this thesis; whereas the MCE is referred to as "deferral repairs". In each case the information recorded by the repairing

activity is entered in a very detailed format so as to facilitate data collection and extraction. A complete analysis of the available deferral data was not pursued. Neither were the Shipboard Alteration Actions, since they were not a direct result of an equipment failure, although they do contribute to workload.

Estimated failure rates, as presented in the RMA Design Data Bank report, Ref. 2., vary a great deal, depending on the data used for estimation: from equipment specification requirements, results of predictions, test results, to measurements during fleet use of the equipments. One of the reasons for the variations is that actual operating time of the equipments in fleet use is rarely known and thus real-time data can not be accumulated except under test situations.

For use in a model we have analyzed the previously described data set (MDCS) in order to obtain meaningful times between failure on the equipments of interest. A brief description of some of the complexities involved in this simplified system might aid the reader in understanding the problems involved in computing failure rates of equipments from fleet (3-M/MDCS) data. Two of the eleven equipments modeled were without a spare, three were substitutable for each other and the remaining equipments had at least one spare available.

All data were first sorted by EIC and then by UIC. Times between failure were computed using several different methods in the process of investigating the data. The author first computed the time between successive failures of like equipment aboard the same ship. This was done by chronologically ordering the failure dates on each ship for each equipment and then computing the desired statistics. This process was done for both failure-only items and for failures and reduced capability items. The second method chosen was to investigate each specific equipment as identified by serial number aboard each ship. The data were sorted by EIC, which identifies the equipment type, UIC, which identifies the ship or unit doing the repair, serial number, and chronological ordering of failure dates and were then used to compute the MTBF for each equipment by taking the difference between the I^{th} failure date and the $(I-1)^{th}$ repair completion date for each set of qualifying records.

The next fourteen pages consist of statistical summary tables and explanation pages for each table indicating what the author thought was important on each table. The following definitions are used throughout the tables:

MTTR	is the Mean Time To Repair as computed from the data
MTBF	is the Mean Time Between Failures as computed component by component
S.D.	is the Sample Standard Deviation
M	is the Sample Size

TABLE I.

MTTR BY RATING GROUPS OF THOSE EQUIPMENTS REPAIRED IN LESS THAN OR EQUAL TO ONE DAY DURING NORMAL REPAIR (IN MAN-HOURS)

EQUIPMENT IDENTIFICATION CODES

RATING GROUPS		QB1J	QB3A	QD3R	QD3S	QD48	QE1N	QF0Q	QF1K	QF10	QF18	Q33K
ETN2	MTTR	4.41	2.38	3.79	4.32	3.74	3.67	2.20	3.46	2.46	3.65	
	S.D.	4.21	2.69	3.77	4.33	2.91	4.50	2.55	4.51	4.13	4.61	
	M	40	833	3356	1438	25	599	293	300	575	57	
FTN3	MTTR	2.61	2.11	3.61	3.81	3.35	3.44	1.99	2.99	2.27	3.67	
	S.D.	2.80	2.77	3.82	4.01	2.91	4.47	1.91	5.09	2.70	3.97	
	M	58	1128	4526	1164	43	714	96	175	456	22	
ET1	MTTR		2.45	3.85	4.08		4.09	2.05	2.74	1.87	3.39	
	S.D.		2.96	4.01	4.50		6.30	1.68	3.91	2.78	4.99	
	M		93	322	148		138	147	210	378	30	
ETR2	MTTR	2.88	2.02	3.91	4.17		3.56	2.18	3.24	1.85	5.20	
	S.D.	3.44	2.60	4.26	3.62		5.73	2.25	5.19	2.30	8.29	
	M	12	224	961	271		139	117	259	793	20	
ETR3	MTTR	3.08	1.71	3.56	3.52		3.00	2.67	3.21	1.36	3.48	
	S.D.	2.12	1.75	4.20	3.91		4.61	3.54	4.33	2.14	4.21	
	M	16	170	793	267		84	69	103	748	12	
RM2	MTTR		3.22	1.99			2.17			1.09	1.68	1.54
	S.D.		7.79	2.45			4.65			1.26	2.76	1.80
	M		52	59			14			51	11	169
RM3	MTTR		1.43	2.43						1.27		1.75
	S.D.		2.00	4.19						2.05		1.98
	M		23	12						26		97
RM1	MTTR	6.03	1.59	3.43			4.03	2.66	3.75	1.51	4.26	1.26
	S.D.	10.99	1.68	5.68			6.02	1.61	5.47	3.14	7.19	2.99
	M	12	98	163			69	20	19	443	55	408

The entries in Table I. are (a) the mean time to repair each respective equipment by each listed repairman rating along with (b) the sample standard deviation and (c) the sample size. The data were sorted to reflect those repairs taking place immediately by, first, only looking at CSMA records and, second, using only those records which indicated repair was completed in a time less than or equal to one day.

ETN2 and ETN3 rating groups were involved in the majority of all repair actions shown. The mean time to repair within each similar set of ratings for each equipment is essentially the same, when small sample sizes are disregarded.

The MTTR from this table were used as input for the optimistic normal repair rates in the model that is used to predict system availability. The MTTR in hours indicated in this table could reflect an immediate diagnosis of the cause of failure, no delay in getting parts and a successful installation.

TABLE II.

MTTR BY RATING GROUPS OF THOSE EQUIPMENTS REPAIRED IN TWO TO FOUR DAYS DURING NORMAL REPAIR (IN MAN-HOURS)

EQUIPMENT IDENTIFICATION CODES

RATING GROUPS		QB1J	QB3A	QD3R	QD3S	QD48	QE1N	QF0Q	QF1K	QF10	QF18	Q33K
ETN2	MTTR		3.07	6.53	8.23		9.09	6.05	9.12	5.04	12.71	
	S.D.		3.59	7.07	8.26		10.68	8.46	10.95	8.34	15.41	
	M		165	751	362		133	33	67	105	11	
ETN3	MTTR		2.98	6.53	7.37	10.28	7.24	4.44	4.92	5.56		
	S.D.		4.28	7.92	7.88	8.72	10.00	6.67	7.06	8.29		
	M		215	999	386	12	140	23	50	78		
ET1	MTTR		3.39	7.52	7.19		12.76	2.93	3.98	5.40		
	S.D.		2.99	8.55	6.14		13.37	2.73	7.76	7.61		
	M		33	58	45		40	29	44	49		
ETR2	MTTR		1.82	5.38	8.17		8.98	3.38	7.22	5.68		
	S.D.		1.96	5.83	7.85		11.43	5.02	8.88	8.37		
	M		42	165	49		27	22	43	75		
ETR3	MTTR		2.97	6.53	6.59		8.41	5.85	8.15	3.92		
	S.D.		2.81	6.16	6.62		13.39	11.08	9.32	4.86		
	M		34	148	70		14	23	15	76		
RM2	MTTR		7.30	5.40						1.62		2.92
	S.D.		6.78	5.01						2.16		6.04
	M		10	10						16		18
RM3	MTTR											5.08
	S.D.											5.12
	M											19
RM1	MTTR		1.59	8.01					2.86	4.10		2.68
	S.D.		1.32	11.96					3.68	7.89		2.94
	M		15	36					14	46		37

The entries in Table II. represent the mean time to repair each respective equipment by each listed repairman rating along with the sample standard deviation and sample size. The data were sorted to reflect only those records of equipments entering normal repair by only looking at CSMA records and, second, using only those records which indicated repair was completed in greater than or equal to two days and less than or equal to four days from the discovery of equipment failure. The longer time period to complete repair of equipment in this case could be thought of as being the result of a complicated failure which could not be immediately diagnosed. This is somewhat supported by the fact that in almost every case in Table II. the repair times are greater than in Table I., and in the majority of cases, greater by fifty percent or more. If the two to four day delay were solely attributable to waiting for parts, then the man-hours expended should have been more in line with Table I., since it took significantly longer, one would tend to believe the initial premise of a complicated failure followed by a more involved repair action.

TABLE III.

MTTR BY RATING GROUPS OF THOSE EQUIPMENTS REPAIRED IN FIVE OR MORE DAYS DURING NORMAL REPAIR (IN MAN-HOURS)

EQUIPMENT IDENTIFICATION CODES

RATING GROUPS		QB1J	QB3A	QD3R	QD3S	QD48	QE1N	QF0Q	QF1K	QF10	QF18	Q33K
ETN2	MTTR	5.76	2.69	5.78	6.69	6.91	6.76	2.31	5.43	2.68	4.72	5.35
	S.D.	6.95	4.32	7.66	9.25	10.31	9.62	3.94	9.48	4.77	7.68	10.77
	M	135	1581	2612	1034	28	706	545	458	931	71	19
ETN3	MTTR	4.93	2.65	5.38	4.99	5.03	4.81	2.68	3.26	2.70	2.83	.95
	S.D.	7.47	4.22	7.36	6.90	4.60	7.56	3.95	4.14	4.20	3.96	1.44
	M	114	2177	3414	1335	32	858	257	252	609	32	10
ET1	MTTR	4.01	2.56	4.74	4.40		6.91	2.19	4.27	2.52	4.09	1.79
	S.D.	6.97	4.79	6.17	6.83		10.80	3.52	7.93	5.08	7.54	2.83
	M	48	419	458	198		257	382	333	692	32	23
ETR2	MTTR	3.82	2.70	5.45	5.38		5.87	1.68	4.55	2.80	6.97	
	S.D.	4.46	4.07	6.91	7.71		8.24	2.15	7.97	5.39	13.15	
	M	32	434	747	239		216	385	287	606	35	
ETR3	MTTR	4.48	2.48	6.33	6.68	2.52	4.95	2.64	3.96	2.27	3.44	
	S.D.	4.77	3.94	8.41	7.94	2.95	8.27	5.18	6.84	3.46	8.64	
	M	26	300	486	157	10	100	188	113	496	32	
RM2	MTTR	1.59	1.48	2.36	0.81		3.06	1.66	3.85	1.47	1.56	4.73
	S.D.	2.07	3.91	5.48	1.08		8.07	1.91	8.91	2.02	2.98	7.92
	M	17	132	158	52		78	88	46	267	27	520
RM3	MTTR		1.53	1.71	0.92		1.18	0.89	3.25	1.23		2.74
	S.D.		2.12	3.19	0.78		1.64	1.13	4.34	2.02		4.01
	M		96	70	41		46	21	22	104		215
RM1	MTTR	1.47	1.73	3.38	2.55		3.26	1.59	3.37	1.70	3.71	3.73
	S.D.	1.97	4.16	7.08	6.05		6.57	4.39	6.60	4.22	5.65	6.10
	M	38	214	277	44		165	177	192	639	45	644

The entries in Table III. represent the mean time to repair each respective equipment by each listed repairman rating along with the sample standard deviation and sample size. The data were sorted to reflect only those records of equipments entering normal repair by only looking at CSMA records and, second, using only those records which indicated repair was completed in greater than or equal to five days from discovery of equipment failure.

The repair times shown in this table are significantly greater in almost every case than those in Table I., as might be expected.

What is more suprising is that the repair times in Table III. are generally less than those in Table II. This could reflect a delay of some sort on less complex jobs than those in Table II., either for parts or for outside assistance, and most likely does since all repair actions take five or more days even though the average number of hours to repair the equipment was less than in Table II. Another point of interest is that a higher percentage of repairmen of the RM and ETR groups worked on the equipment under Table III. conditions than in Table I. or Table II. This could be the result of a less complex repair action delayed for parts.

The main item of importance to notice here is that, even though the time to complete the repair action was greater than or equal to five days the MTTR in man-hours expended is still only from one to seven hours, which helps support the tenet that a lot of time is spent waiting for parts or waiting for other specific conditions in order to get started with the job at hand.

TABLE IV.

MTTR BY RATING GROUPS OF THOSE EQUIPMENTS PLACED IN DEFERRAL REPAIR (IN MAN-HOURS)

EQUIPMENT IDENTIFICATION CODES

RATING GROUPS		QB1J	QB3A	QD3R	QD3S	QD48	QF1N	QF0Q	QF1K	QF10	QF18	Q33K
ETN2	MTTR	5.43	2.62	4.97	5.68	6.15	5.68	2.42	5.04	2.73	4.91	4.38
	S.D.	6.43	3.82	6.24	7.18	8.86	8.21	3.88	8.33	4.89	7.83	9.72
	M	183	2579	5000	2833	55	1436	876	823	1627	139	24
ETN3	MTTR	4.12	2.49	4.59	4.69	5.05	4.44	2.59	3.31	2.72	3.49	2.46
	S.D.	6.28	3.79	6.07	5.91	5.25	6.81	3.79	6.06	4.18	4.21	4.55
	M	178	3512	5000	3382	89	1708	379	478	1140	59	12
ET1	MTTR	3.94	2.57	4.59	4.64		6.54	2.15	3.70	2.42	3.83	1.91
	S.D.	6.54	4.24	5.71	6.06		10.15	3.08	6.79	4.64	6.63	2.74
	M	59	551	840	394		434	565	586	1120	69	26
ETR2	MTTR	3.72	2.43	4.63	5.01		5.24	1.83	4.17	2.44	7.09	
	S.D.	4.16	3.57	5.61	6.18		7.83	2.33	7.04	4.37	11.81	
	M	46	700	1880	560		383	521	588	1473	58	
ETR3	MTTR	4.31	2.24	4.81	5.04	3.93	4.38	2.90	3.91	1.85	4.79	
	S.D.	4.18	3.30	6.31	6.09	4.70	7.58	5.61	6.16	2.98	9.79	
	M	48	505	1423	492	20	19[illegible]	281	230	1321	48	
RM2	MTTR	1.53	1.91	2.40	0.79		3.24	1.68	3.37	1.56	1.53	3.93
	S.D.	1.96	5.20	4.86	1.07		7.86	1.98	8.06	3.28	2.72	7.04
	M	19	194	230	54		99	95	58	336	43	707
RM3	MTTR	0.59	1.52	1.78	0.89		1.19	0.97	3.15	1.22		2.58
	S.D.	0.40	2.07	3.24	0.78		1.59	1.07	4.17	1.99		3.68
	M	12	121	88	43		50	24	24	134		333
RM1	MTTR	2.58	1.67	3.73	3.73		3.63	1.90	3.37	1.73	3.92	2.77
	S.D.	5.83	3.49	7.22	7.02		6.47	4.49	6.33	4.08	6.50	5.19
	M	50	328	475	50		240	204	227	1133	100	1092

The entries in Table IV. represent the mean time to repair each respective equipment by each listed repairman along with the sample standard deviation and sample size. The data were sorted to reflect those repairs listed as deferrals resulting from operational priority, lack of material, or the necessity of obtaining outside assistance. This sort was accomplished by looking at MCE records and all repair times.

ETN2 and ETN3 rating groups were again involved in the majority of all repair actions; however, the ET1, ETR2 and ETR3 rating groups number of repair actions increased considerably over those listed in Table I. Again, within broad rating groups the MTTR were essentially the same. The MTTR entries only reflect the man-hours required to fix the equipment and thus does not reflect the average time to complete repair of 64 days for all deferral actions taken as a class. This large difference in time required to complete a repair action is thought to consist mostly of waiting time for parts or outside assistance.

TABLE V.

MTBF OF THOSE EQUIPMENTS FAILING IN LESS THAN 365 DAYS FROM THE TIME OF LAST REPAIR BY THE RATING GROUP OF THE REPAIRMAN WHO MAINTAINED THE EQUIPMENT IMMEDIATELY PRIOR TO FAILURE (IN DAYS)

EQUIPMENT IDENTIFICATION CODES

RATING GROUPS		QB1J	QB3A	QD3R	QD3S	QD48	QE1N	QF0Q	QF1K	QF10	QF18	Q33K
ETN2	MTBF	129.61	105.31	81.16	94.59		96.93	101.46	93.37	61.48	29.35	
	S.D.	111.78	97.23	84.31	89.93		99.06	96.61	89.11	77.73	39.76	
	M	13	183	1878	725		353	105	143	160	23	
ETN3	MTBF		124.25	81.89	93.72	108.20	95.75	129.29	89.20	87.27	17.87	
	S.D.		106.23	86.99	91.51	110.87	98.37	122.70	89.96	95.97	44.64	
	M		265	2779	936	10	490	24	98	150	15	
ET1	MTBF		95.61	89.27	89.38		86.39	80.58	76.32	53.25		
	S.D.		94.94	89.61	79.63		92.25	86.67	89.62	59.40		
	M		23	131	53		87	52	127	156		
ETR2	MTBF		126.87	77.00	86.03		88.13	63.21	55.82	70.13		
	S.D.		99.39	86.11	89.59		95.12	73.22	76.78	83.17		
	M		46	619	134		79	39	155	375		
ETR3	MTBF		87.56	74.73	107.75		114.30	77.14	63.30	63.27		
	S.D.		103.57	83.72	96.07		108.07	102.69	80.12	83.33		
	M		45	494	145		60	21	56	411		
RM2	MTBF									71.38		91.69
	S.D.									101.41		116.83
	M									16		51
RM3	MTBF											56.71
	S.D.											85.09
	M											28
RM1	MTBF		142.70	103.17			126.53		124.88	42.20	54.64	48.47
	S.D.		113.65	114.50			126.09		90.57	66.63	69.82	79.32
	M		10	30			13		16	148	11	145

The data used to derive Table V. were sorted in such a manner that only those failures occurring within 365 days of the previous repair action were utilized. This method tends to give a conservative estimate of the MTBF. Each equipment type was looked at component by component so as to get the most information about failure time from the data; i.e., list all the maintenance actions on one piece of equipment in chronological order and record the time between completion of last repair and the next failure, when the process is out of data on that particular piece of equipment, start again with the next one.

The data used to derive Table VI. were sorted by components that either failed or were listed in a reduced capability status during a 365 day time span from the completion of the last repair of each component. This method in general yielded shorter MTBF than those looking at failures alone, such as on Table V. It should be noted that the sample for each catagory in this table includes the complete sample used in Table V.

TABLE VI.

MTBF OF THOSE EQUIPMENTS EITHER FAILING OR EXPERIENCING REDUCED CAPABILITY IN LESS THAN 365 DAYS FROM THE TIME OF LAST REPAIR BY THE RATING GROUP OF THE REPAIRMAN WHO MAINTAINED THE EQUIPMENT IMMEDIATELY PRIOR TO FAILURE OR REDUCED CAPABILITY (IN DAYS)

EQUIPMENT IDENTIFICATION CODES

RATING GROUPS		QB1J	QB3A	QD3R	QD3S	QD48	QE1N	QF0Q	QF1K	QF10	QF18	Q33K
ETN2	MTBF	113.79	113.00	70.83	84.66	50.17	87.29	100.46	93.23	75.95	34.72	
	S.D.	92.25	101.56	77.12	85.24	54.07	90.41	97.89	89.32	88.66	51.89	
	M	19	481	3358	1370	12	548	130	176	265	25	
ETN3	MTBF	126.60	118.23	74.23	83.06	73.78	89.65	124.39	86.37	93.85		
	S.D.	106.11	103.34	83.87	83.80	92.82	92.57	119.69	89.82	101.64		
	M	15	806	4628	1631	36	691	33	118	216		
ET1	MTBF		123.46	74.41	77.06		83.15	92.59	74.85	63.57	17.19	
	S.D.		102.88	80.66	71.81		89.56	97.13	87.05	72.05	43.21	
	M		67	290	124		136	67	148	207	16	
ETR2	MTBF		136.81	72.54	79.03		75.79	71.13	56.54	64.50		
	S.D.		107.67	82.47	85.35		83.15	78.96	76.91	80.79		
	M		123	1020	242		132	47	176	422		
ETR3	MTBF		107.56	68.08	92.78		92.30	83.45	63.22	62.61	82.50	
	S.D.		99.56	78.31	86.24		96.94	85.82	79.28	81.86	92.01	
	M		94	777	243		83	29	63	454	10	
RM2	MTBF		135.77	119.05			67.69			98.11		103.60
	S.D.		93.68	113.46			91.98			115.11		113.57
	M		22	41			13			27		101
RM3	MTBF											81.28
	S.D.											55.43
	M											57
RM1	MTBF		122.80	101.52			141.00		133.91	48.74	58.79	41.59
	S.D.		98.14	101.82			120.19		100.34	80.25	81.87	70.26
	M		51	109			42		22	254	19	286

TABLE VII.

AGGREGATE MTBF, MTTR, AND PROBABILITY OF ENTERING NORMAL REPAIR (MTBF AND MTTR ARE IN DAYS)

EQUIPMENT IDENTIFICATION CODES

RATING GROUPS	QB1J	QB3A	QD3R	QD3S	QD48	QE1N	QF09	QF1K	QF10	QF18	Q33K
MTBF 1.	127.48	114.92	78.82	93.78	73.56	94.85	93.47	79.18	64.43	36.85	60.75
	101.65	103.54	85.36	91.12	98.68	97.98	95.60	87.87	80.69	58.20	91.02
	31	629	5000	2125	16	1146	265	629	1489	68	229
MTBF 2.	119.05	116.96	67.60	83.19	66.98	87.74	96.20	79.75	67.53	48.24	65.17
	96.06	102.29	80.62	84.40	79.87	91.62	96.99	88.21	84.57	71.06	91.59
	59	1824	5000	3878	56	1736	337	744	2002	90	471
MTTR 3.	13.55	12.82	6.45	6.78	12.74	9.24	4.71	6.60	3.98	2.99	3.34
	32.64	34.16	19.30	21.17	31.20	27.56	15.97	25.53	15.03	13.63	12.25
	162	2347	5000	3843	57	2148	797	1310	3203	193	380
MTTR 4.	92.07	69.84	64.63	55.07	54.04	63.34	68.32	57.50	57.67	65.76	65.04
	88.32	70.78	69.43	62.67	53.05	64.76	74.23	72.15	67.04	83.53	75.47
	113	1342	1992	760	28	812	348	547	972	62	383
MTTR 5.	16.99	12.94	5.84	6.25	10.40	9.94	5.67	7.50	4.38	3.14	4.97
	40.86	35.20	17.35	20.03	27.89	27.89	20.06	27.85	16.29	13.09	20.72
	225	4195	5000	5000	120	2784	909	1464	3923	227	635
MTTR 6.	99.83	78.61	72.33	64.82	49.85	73.46	77.85	67.29	65.89	73.68	71.64
	88.62	74.93	74.43	68.53	47.65	74.65	81.22	80.05	72.52	87.02	79.30
	213	3051	3809	1398	40	1251	533	764	1609	102	810
7.	.43	.52	.75	.74	.68	.63	.35	.51	.53	.48	.35

1. Failures
2. Failures and Reduced Capabilities
3. Failures Receiving Normal Repair
4. Failures Receiving Deferral Repair
5. Failures and Reduced Capabilities Receiving Normal Repair
6. Failures and Reduced Capabilities Receiving Deferral Repair
7. Probability of Entering Normal Repair

Table VII. is the most general table of all, and could quite possibly contain the most enlightening information also. Rows one and two are straightforward MTBF in days. Row three entries are the mean time to complete a repair of a failure for all actions listed as organizational level and ready for immediate repair. A range of three to thirteen days makes it rather hard to believe the often quoted MTTR in terms of hours as indicated in Tables I - IV. It should also be pcinted out that over 75% of the observations were actually less than each of the respective MTTR computed which is also indicated by the large standard deviations compared to the location of the mean.

If times to repair were exponentially distributed, one would expect $1 - e^{-(1/MTTR)(MTTR)} = 0.63$ or 63% of the observations to be less than the MTTR, this along with the larger standard deviations lend support to saying that repair times tend to be "hyper exponential", having very long tailed distributions.

Similar reasoning may be applied to row five, which contains both failures and reduced cabability records. Rows four and six depict deferral type maintenance information on the MTTR for each respective equipment. One could infer that these long MTTR in days were the result of waiting for parts or outside assistance.

The probability of entering normal repair as listed in row seven was computed by summing over all maintenance actions of each equipment type (different EIC), the total number of MCE (deferral repair actions) and the total number of CSMA (normal repair actions). The entry in row seven was then computed to be CSMA/(CSMA + MCE).

IV. REPAIRMAN TYPE MODEL

Individual pieces of equipment can fail and either enter normal repair or enter deferral repair with some specified probability for each type of equipment. Equipment failures are repaired on a First-Come - First-Served basis. If a failure occurs and is not repaired, the system is subject to failure. When enough failures occur so as to saturate the available number of repairmen, a repair queue begins to build up of those equipments waiting to be repaired. Equipments which can not be repaired due to lack of material (parts) or lack of technical expertise are placed in a deferral repair status and generally experience an extremely long delay before the situation can be remedied.

The deferral repair time distributions from Table VII. could be used as parameters not really dependent on the number of repairmen available and thus can be considered in service concurrently with the normal repair actions. Thus a generalized view of this model is that when equipment fails it is either repaired quickly or is delayed for some reason. The probability of being in any particular situation is an output of the model developed here.

This model is based upon a simplification of the maintenance process and is designed to utilize the results of the data investigation of Chapter III, or any other variation a user might desire. One, two or three repairmen may be specified to work on any number of equipments. The model is more realistic than other repairman type models in that it allows for individualized failure rates and repair rates for each type of equipment. Different deferral probabilities for each equipment are also allowed. These additional features of the model, while increasing the realism of the problem, also increase the complexity of the solution as indicated by Gaver in Ref. 3.

Incorporating manpower data and equipment reliability data into a model was predicated on considerations in three major areas:

(1.) availability of sufficient and meaningful data,

(2.) ability to vary factors of interest to Navy planners,

(3.) measures of system performance.

Availability of data has been previously discussed in Chapter III. Factors of interest to the Navy planners were manning levels, manning effectiveness and equipment reliability and availability. The effect of changed overall manning levels on mission success can be studied by using differing numbers of repairmen in the model.

The primary measure of system performance was taken to be the probability of mission success, or one minus the probability of mission failure.

A. INPUT ASSUMPTIONS

The individual times between failures, times to complete repairs, and times to complete deferred repairs are assumed to be independently and exponentially distributed. This assumption seems credible as indicated in Chapter III, where the number of observations examined was greater than three to four hundred. Basic parameters appearing in the models are the MTBF for equipments as well as MTTR (normal, and deferred).

Each equipment fails at a different but constant rate F_i (i=1,2,...,N), and can be repaired at the normal (immediate) repair rate R_i (i=1,2,...,N) or at the deferral repair rate RD_i (i=1,2,...,N). Each equipment is assumed to go into immediate repair with probability p_i or deferral repair with probability $q_i=1-p_i$ (i=1,2,...,N). These rates and probabilities were determined from the data of Chapter III.

Deferral repair action MTTR over all equipment types ranged from 54 to 92 days to repair a failure. This long time was thought to be a result of waiting for parts or outside assistance. The MTTR computed here was so

much greater than the MTTR for normal repairs (10 to 60 times longer) that the author decided to use the MTTR for deferrals as a repair time not influenced by actual repairman time. In other words, deferral repairs could be going on simultaneously with normal repairs even though all the repairmen were busy. This is due to the long waiting time involved in a deferral action relative to the actual time required to fix a piece of equipment.

B. SYSTEM STATES

Normally, order of failure is important in determining when an equipment begins to get repaired. This has not changed in this model, the first item to fail and enter into the immediate repair queue is serviced first. In practice a priority scheme might be followed.

1. Finite Capacity Assumption

Three failures of any type are all that are allowed. This restriction can be changed by incorporating additional echlons of state spaces into the model. Allowing only three simultaneous failures was considered adequate, since only eleven or twelve pieces of equipment were modeled as a sub-system.

2. Labeling of States

The order in which failures occur define the label of each possible state for the system to be in.

The states of this model may be identified according to the following format:

N is the number of different equipments labeled from 1 to N.

$i \neq j \neq k$	$(i,j,k=1,2,\ldots,N)$
(o)	no equipment failures
(i)	equipment number i has failed and is in normal repair
(iD)	equipment number i has failed and is in deferral repair
(i,j)	equipment number i has failed first and is in normal repair, equipment number j has failed second and is in normal repair
(i,jD)	same as (i,j) with j in deferral repair
(iD,j)	same as (i,j) with i in deferral repair
(iD,jD)	same as (iD,j) with j in deferral repair
(i,j,k)	same as (i,j) with equipment number k has failed third and is in the normal repair queue
(i,j,kD)	same as (i,j,k) with k in the deferral repair queue
(iD,jD,k)	same as (i,j,k) with i and j in the deferral repair queue
(iD,jD,kD)	same as (i,j,k) with i, j, and k all in the deferral repair queue

State (3,4D,7) would mean that equipment number 3 had failed first and is in the normal repair queue, equipment number 4 had failed second and is in the deferral repair queue, and equipment number 7 had failed third and is in the normal repair queue.

Each piece of equipment to be modeled is assigned a unique equipment number and thus if there are several pieces of the same equipment, each has a unique number even though the failure and repair rates are identical for each equipment.

C. BALANCE EQUATIONS

The balance equations equate the rate at which the system enters a certain state to the rate at which the system leaves that state. Now using the previously defined states and parameters, the following balance equations for two repairmen are written as a selection from the entire system. Where, as an example, $P_{jD,i}$ means the probability of being in state (jD,i). The total number of states is equal to 1+2(N)+4(N)(N-1)+8(N)(N-1)(N-2) for this model.

$$\left(\sum_{i=1}^{N} F_i\right) P_o = \sum_{i=1}^{N} R_i P_i + \sum_{i=1}^{N} RD_i\, P_i$$

$$\left(R_i + \sum_{j\neq i}^{N} F_j\right) P_i = P_o p_i F_i + \sum_{j\neq i}^{N} R_j P_{j,i} + \sum_{j\neq i}^{N} RD_j P_{jD,i}$$

This is to say that the only way to get into state (i) is to be in state (o) and have equipment i fail and go into normal repair or to be in state (j,i) or (jD,i) and have equipment j repaired. The only way to leave state (i) is to either have equipment i fixed or to have a failure of another equipment.

$$\vdots$$

$$(R_i + RD_j + \sum_{k\neq i\neq j}^{N} F_k)\, P_{i,jD} = P_i q_j F_j + \sum_{k\neq i\neq j}^{N} R_k P_{k,i,jD} +$$
$$\sum_{k\neq i\neq j}^{N} RD_k P_{kD,i,jD}$$

$$\vdots$$

$$(R_i + R_j + 0)\, P_{i,j,k} = P_{i,j} p_k F_k$$

Only allowing three failure yields the above equation, since there are only two repairmen.

$$\vdots$$

$$(RD_i + RD_j + RD_k)\, P_{iD,jD,kD} = P_{iD,jD} q_k F_k$$

Here it is noted that three deferrals are being serviced even though there are only two repairmen. This is due to the assumption about deferral repair actions.

D. SOLUTION TECHNIQUE

The Gauss-Seidel iterative approach to the steady state solution of a system of balance equations was used. Briefly, this approach is as follows:

1. Initiate Starting State Probabilities

The most convenient assignment method is to use an equally likely distribution and assign each the value 1.0/(total number of states).

2. Turn the Crank

Using the present values for each state, solve for P_0 and use the new value for P_0 when solving any additional equations containing P_0. This same method is then used for P_1 and all of the other possible states. Continue until a new probability has been computed for each state.

3. Normalization

Take the sum of all of the new probabilities just computed and divide it into each of the new probabilities, thus ensuring that all probabilities add to unity, as they must.

4. Check for Stopping Criteria Satisfaction; Re-iteration

The author chose to use a relative ratio method to test for a minimal change in probabilities, since many of the probabilities would be extremely small and would thus always pass a simple differencing technique. The method was to take the absolute value of the difference between the old probability and the newly computed probability and divide by the new probability. (| OLD-NEW | /NEW) This was done for each state and checked to see if the

result was greater than 0.0001. If so, for at least one state, the iterative process must continue until all states pass the stopping criteria; i.e., GO TO 2 and start again.

V. RESULTS

The model was programmed in Fortran G and was executed to generate the results listed here. The computer listing follows Appendix A. The output of this model comes in the form of long run probabilities of being in any particular state. Selected sorting and summing procedures are then used to produce the probability that any set of equipments are down, and thus it is possible to calculate the probability that the system is down. This was done for each of the sets of equipment described in Figure 2 and then the joint probability was computed and used in the results. As an example of the size of the sorting and summing task: using N=12 equipment yields 11,113 different possible states which are then easily sorted and summed on a computer by user supplied logic statements specific to the information desired.

The author chose to present two of the multitude of possible outcomes in the Results section.

A. SPECIFIC RESULTS

1. Optimistic

Using the normal repair times (Table I.), probabilities of entering normal repair (Table VII.), and the deferral repair times for failures (Table VII.) resulted in the following:

Probability that all equipment are up = 0.4220

Probability of system unavailability = 0.1185

Where system down means that at least one subsystem or mission capability can no longer function due to equipment failure. It should be pointed out that the other seven sub-systems could quite possibly be available.

2. Pessimistic

Using the normal repair times for failures (Table VII. row 3), and keeping all other parameters the same as the optimistic case.

Probability that all equipment are up = 0.0988

Probability of system unavailability = 0.3086

3. More Realistic

A weighted average of times to repair each equipment was used to compute the MTTR used as input for this calculation. The method of weighting was as follows: (1) sort the data to reflect only normal repair records; (2) extract a frequency distribution of the number of days to repair a failed equipment;

(3) use this distribution to compute the weightings for each of the equipments. The time-to-repair factor for the one-day-or-less category was the time in hours from Table I. times the percent of normal repair actions occurring in one day or less. The time to repair factor for the two-to-four day category was 48 hours times the percent of normal repair actions in that category. The time to repair factor used for the five-or-more days category was the MTTR for failure-only undergoing normal repair from Table VII. Since the MTTR was listed in days, it was converted to hours and multiplied by the percent of normal repairs occurring in five or more days.

Generally, the percentages for each category were about: 65% in one or less days; 10% in two to four days; and 25% in five or more days. The results of using this input was as one would expect, in-between the optimistic and pessimistic cases.

Probability that all equipment are up = .3025

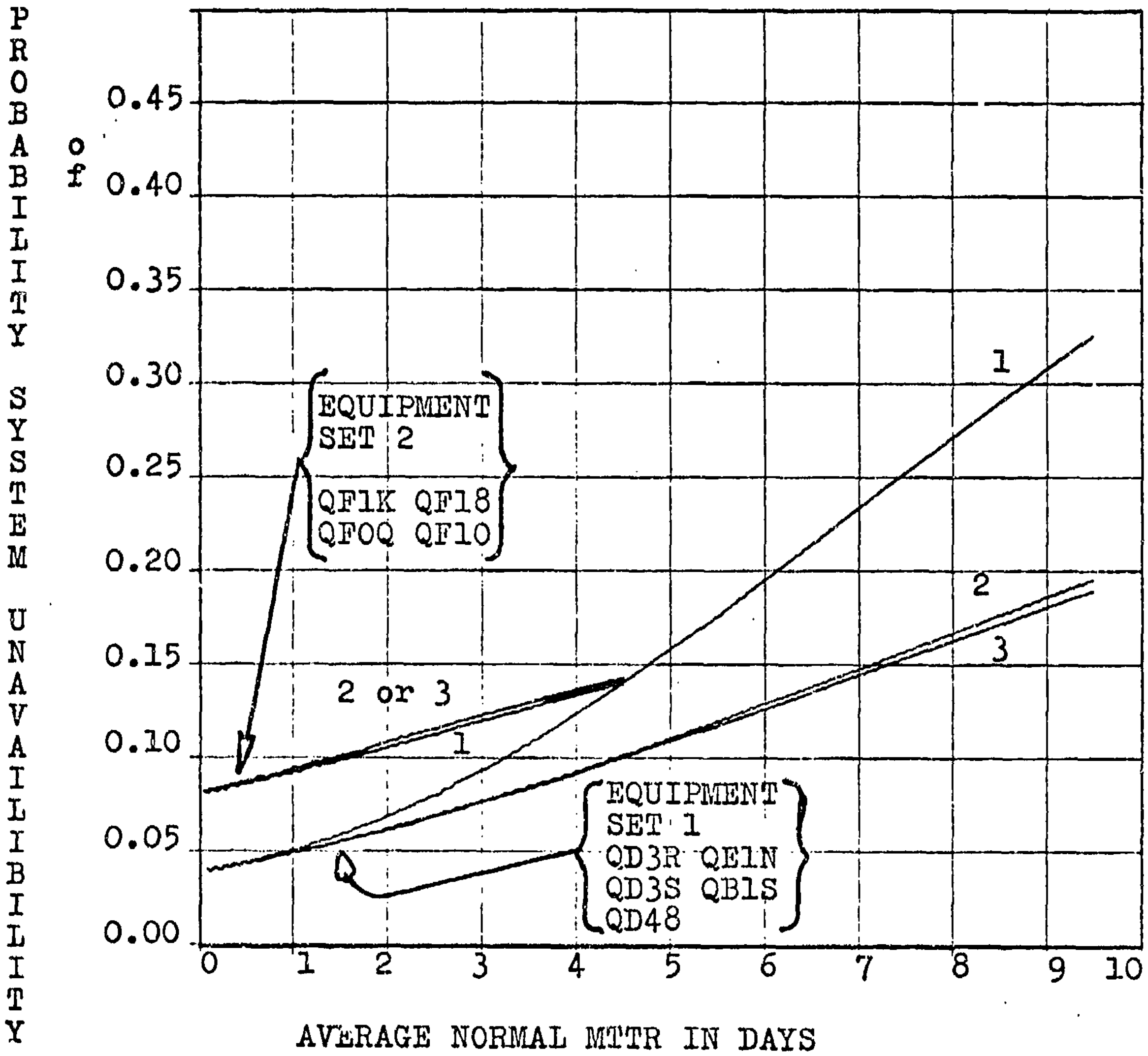
Probability of system unavailability = .1543

B. RESULTS OF VARYING NORMAL REPAIR TIMES

The following graphs were made to show the complete range of good to bad repair times and their effect on mission failure.

Figure 2.

Graph of System Unavailability Versus Average MTTR and Manning Level



The numerals nearest the lines indicate the number of repairmen used.

Figure 2. presents both equipment sets using 1,2 and 3 repairmen, over the full range of optimistic to pessimistic values for the normal MTTR. There appears to be very little difference in results between using two or three repairmen on Equipment Set 1 and thus two repairmen would be preferred. There was essentially no difference in results between the differing number of repairmen on Equipment Set 2 and thus one repairman would be preferred. The realistic estimates for these sets of equipment varied from; a MTTR of 2.75 days and a system down probability of 0.08 for 1 repairman to 0.07 for 2 or 3 repairmen on Equipment Set 1, to a MTTR of 0.88 days and a probability of the system being down of 0.09 for 1,2 or 3 repairmen. It was noted that 1 repairman on Set 2 produced very slightly better results than two or three repairmen; this was considered to be a result of computer roundoff error since there was essentially no difference between them.

VI. CONCLUSIONS

Useful failure rate and repair time parameters can be extracted from 3-M data. Simplified systems of critical equipments and the associated repairmen can be modeled to estimate a specified mission probability of sucess.

The long time to complete deferral repairs are basically the limiting factors in computing mission success or failure; i.e., the probability that the system is down reaches a limiting value does not decrease no matter how fast an item can be fixed in normal repair. This would seem to imply that in order to get more equipment repaired faster, the deferral repair times need to be reduced.

This model can be expanded to look at cases allowing more than three failure quite easily, the only note of caution is that as additional failures are included the number of possible states increases too, which may at some point become too unweidly to handle.

It is the author's recommendation that further investigation into simplification modeling of systems be looked at in other areas in an effort to reduce modeling costs without sacrificing the desired goals of the Navy planners.

APPENDIX A.

List of Acronyms, Abbreviations and Equipments

CSMA	Completed Shipboard Maintenence Action (Normal Repair Form)
EIC	Equipment Identification Code
HF	High Frequency
MCE	Maintenance Closing Event (Deferral Repair Form)
MDCS	Maintenance Data Collection System
MF	Medium Frequency
RCVR	receiver
UHF	Ultra High Frequency
UIC	Unit Identification Code
VLF	Very Low Frequency
XCVR	transceiver
XMTR	transmitter

EIC	Equipment Name	Function
QB1J	AN/WRR-3B	VLF/MF RCVR
QB3A	R-1051	MF/HF RCVR
QD3R	AN/SRC-20	UHF XCVR
QD3S	AN/SRC-21	UHF XCVR
QD48	AN/URC-9	UHF XCVR
QE1N	AN/URT-23	HF XMTR
QF0Q	KG-14	SECURITY
QF1K	KY-8	SECURITY
QF10	KW-7	SECURITY
QF1B	KW-37	SECURITY
Q33K	AN/UGC-20	Teletypewriter

```
C     THIS PROGRAM WILL COMPUTE AND WRITE OUT, IF DESIRED, THE
C     PROBABILITY OF BEING IN ANY STATE AS DEFINED IN THE AUTHOR'S
C     THESIS
C
C     I N P U T   A R R A Y S
C     THE INPUT ARRAYS MAY BE DIMENSIONED LARGER TO HANDLE LARGER
      PROGRAMS, IF DESIRED
      P ARRAY IS THE PROBABILITY OF GOING INTO NORMAL REPAIR
      R ARRAY IS THE NORMAL REPAIR RATE
C     RD ARRAY IS THE DEFERRAL REPAIR RATE
C     F ARRAY IS THE FAILURE RATE
C
      REAL PN(12),P1(12),PD(12),P2(12),Q(12),X(100),Y(100)
      REAL PNN(12,12),P1N(12,12),PND(12,12),P1D(12,12),PDN(12,12),
     *P2N(12,12),PDD(12,12),P2D(12,12)
      REAL PNNN(12,12,12),P1NN(12,12,12),PNND(12,12,12),P1ND(12,12,12),
     *PNDN(12,12,12),P1DN(12,12,12),PNDD(12,12,12),P1DD(12,12,12),
     *PDNN(12,12,12),P2NN(12,12,12),PDND(12,12,12),P2ND(12,12,12),
     *PDDN(12,12,12),P2DN(12,12,12),PDDD(12,12,12),P2DD(12,12,12)
      REAL P(12)/12*0.0/
      REAL R(12)/12*2.0/
      REAL RD(12)/12*2.0/
      REAL F(12)/12*1.0/
C
C     N  IS THE NUMBER OF INDIVIDUAL PIECES OF EQUIPMENT
C     I1,I2,I3,ETC.  ARE VARIABLES USED TO SORT OUT THE VARIOUS
C     PROBABILITIES.  THEY NEED TO BE CHANGED FOR EACH SPECIFIC
C     SET OF EQUIPMENTS.
C     FOR EXAMPLE  I1=2 MEANS THAT THE FIRST TYPE OF EQUIPMENT
C     CONSISTS OF TWO IDENTICAL PIECES, AND ARE STORED IN THE FIRST
C     TWO ELEMENTS OF THE INPUT ARRAYS
C
C     A  IS THE DESIRED PRECISION FOR THE STOPPING CRITERIA
C
      N=12
      I1=2
      I2=6
      I3=8
      I4=12
      M=C
      A=0.0001
      IWRITE=1
C
C     IWRITE = 0  IF PRINTOUT OF ALL POSSIBLE STATE PROBABILITIES
C     IS DESIRED
C     IWRITE = 1  IF ONLY FINAL PROBABILITIES ARE DESIRED
C
C     THIS DO LOOP CHANGES THE NUMBER OF REPAIRMEN FROM 1 TO 3
```

```
C     TAKING OUT THE DO LOOP AND SPECIFYING A VALUE FOR MEN FROM
C     1 TO 3 MAY ALSO BE DONE
C
      DO 810 KLM=1,3
      MEN=KLM
      IF(MEN.NE.3) GO TO 10
      RMAN=1.0
      RMEN=1.0
      GO TO 40
   10 IF(MEN.NE.2) GO TO 20
      RMAN=1.0
      RMEN=0.0
      GO TO 40
   20 IF(MEN.NE.1) GO TO 30
      RMAN=0.0
      RMEN=0.0
      GO TO 40
   30 WRITE(6,950)
      GO TO 1000
   40 CONTINUE
      IF(KLM.GT.1) GO TO 130
C
C     INITIATE VALUES FOR ALL STATES   IC=# OF STATES OF ORDERED FAILURE
C     C= TOTAL # OF POSSIBLE STATES
C
      IC=2*N+4*N*(N-1)+8*N*(N-1)*(N-2)
      C=IC+1
      PO=1.0/C
      TEMP=PO
      DO 120 I=1,N
      PN(I)=PO
      PD(I)=PO
      P1(I)=PO
      P2(I)=PO
      Q(I)=1.0-P(I)
      DO 110 J=1,N
      PNN(I,J)=PO
      P1N(I,J)=PO
      PND(I,J)=PO
      P1D(I,J)=PO
      PUN(I,J)=PO
      P2N(I,J)=PO
      PDD(I,J)=PO
      P2D(I,J)=PO
      DO 100 K=1,N
      PNNN(I,J,K)=PO
      P1NN(I,J,K)=PO
      PNND(I,J,K)=PO
```

```
      P1ND(I,J,K)=PO
      PNDN(I,J,K)=PO
      P1DN(I,J,K)=PO
      PNDD(I,J,K)=PO
      P1DD(I,J,K)=PO
      PDNN(I,J,K)=PO
      P2NN(I,J,K)=PO
      PDND(I,J,K)=PO
      P2ND(I,J,K)=PO
      PDDN(I,J,K)=PO
      P2DN(I,J,K)=PO
      PDDD(I,J,K)=PO
      P2DD(I,J,K)=PO
  100 CONTINUE
  110 CONTINUE
  120 CONTINUE
  130 CONTINUE
      KNTR=0
      ONEDN=0.0
      ONEDM=0.0
      ONEDO=0.0
      ONEDP=0.0
      DN=0.0
      DM=0.0
      DO=0.0
      DP=0.0
C
C     START OF GAUSS-SEIDEL ITERATIONS
C     FIRST SOLVE FOR PO
C
  150 SUM=0.0
      KNTR=KNTR+1
      SF=0.0
      SR=0.0
      SRD=0.0
      DO 200 I=1,N
      SF=SF+F(I)
      SR=SR+R(I)*PN(I)
      SRD=SRD+RD(I)*PD(I)
  200 CONTINUE
      PO=(SR+SRD)/SF
      SUM=SUM+PO
C
C     SOLVING FOR ONE DOWN STATES
C
      DO 300 I=1,N
      SN=0.0
      SD=0.0
```

```
      SF=0.0
      DO 250  J=1,N
      IF(I.EQ.J) GO TO 225
      SF=SF+F(J)
      SF=SF+F(J)
      SN=SN+R(J)*PNN(J,I)  +  RD(J)*PDN(J,I)
      SD=SD+R(J)*PND(J,I)  +  RD(J)*PDD(J,I)
  225 CONTINUE
  250 CONTINUE
      PN(I)=(PO*P(I)*F(I)+SN)/(R(I)+SF)
      PD(I)=(PO*Q(I)*F(I)+SD)/(RD(I)+SF)
      SUM=SUM+PN(I)+PD(I)
  300 CONTINUE
C
C     SOLVING FOR TWO DOWN STATES
C     INCREMENT J DISALLOWING SAME EQUIPMENT FAILING TWICE
C
      DO 400  I=1,N
      DO 350  J=1,N
      IF(I.EQ.J) GO TO 350
      SF=0.0
      SNN=0.0
      SND=0.0
      SDN=0.0
      SDD=0.0
      DO 325  K=1,N
      IF(I.EQ.K) GO TO 325
      IF(J.EQ.K) GO TO 325
      SF=SF+F(K)
      SNN=SNN+R(K)*PNNN(K,I,J)  +  RD(K)*PDNN(K,I,J)
      SND=SND+R(K)*PNND(K,I,J)  +  RD(K)*PDND(K,I,J)
      SDN=SDN+R(K)*PNDN(K,I,J)  +  RD(K)*PDDN(K,I,J)
      SDD=SDD+R(K)*PNDD(K,I,J)  +  RD(K)*PDDD(K,I,J)
  325 CONTINUE
      PNN(I,J)=(PN(I)*P(J)*F(J)+SNN)/(R(I)+RMAN*R(J)+SF)
      PND(I,J)=(PN(I)*Q(J)*F(J)+SND)/(R(I)+RD(J)+SF)
      PDN(I,J)=(PD(I)*P(J)*F(J)+SDN)/(RD(I)+R(J)+SF)
      PDD(I,J)=(PD(I)*Q(J)*F(J)+SDD)/(RD(I)+RD(J)+SF)
      SUM=SUM+PNN(I,J)+PND(I,J)+PDN(I,J)+PDD(I,J)
  350 CONTINUE
  400 CONTINUE
C
C     SOLVING FOR THREE DOWN STATES
C     I CAN NOT EQUAL J WHICH CAN NOT EQUAL K
C
      DO 500  I=1,N
      DO 450  J=1,N
      IF(I.EQ.J) GO TO 450
```

```
      DO 425 K=1,N
      IF(I.EQ.K) GO TO 425
      IF(J.EQ.K) GO TO 425
      PNNN(I,J,K)=PNN(I,J)*P(K)*F(K)/(R(I)+RMAN*R(J)+RMEN*R(K))
      PNND(I,J,K)=PNN(I,J)*Q(K)*F(K)/(R(I)+RMAN*R(J)+RD(K))
      PNDN(I,J,K)=PND(I,J)*P(K)*F(K)/(R(I)+RD(J)+RMAN*R(K))
      PNDD(I,J,K)=PND(I,J)*Q(K)*F(K)/(R(I)+RD(J)+RD(K))
      PDNN(I,J,K)=PDN(I,J)*P(K)*F(K)/(RD(I)+R(J)+RMAN*R(K))
      PDND(I,J,K)=PDN(I,J)*Q(K)*F(K)/(RD(I)+R(J)+RD(K))
      PDDN(I,J,K)=PDD(I,J)*P(K)*F(K)/(RD(I)+RD(J)+R(K))
      PDDD(I,J,K)=PDD(I,J)*Q(K)*F(K)/(RD(I)+RD(J)+RD(K))
       SUM=SUM+PNNN(I,J,K)+PNND(I,J,K)+PNDN(I,J,K)+PNDD(I,J,K)
     *+PDNN(I,J,K)+PDND(I,J,K)+PDDN(I,J,K)+PDDD(I,J,K)
  425 CONTINUE
  450 CONTINUE
  500 CONTINUE
C
C     NORMALIZATION PROCESS STARTS HERE
C
      IFLAG=0
      PO=PO/SUM
      IF(ABS(TEMP-PO)/PO.GT.A) IFLAG=1
      TEMP=PO
      DO 600 I=1,N
      PN(I)=PN(I)/SUM
      PD(I)=PD(I)/SUM
      IF(ABS(P1(I)-PN(I))/PN(I).GT.A) IFLAG=1
      IF(ABS(P2(I)-PD(I))/PD(I).GT.A) IFLAG=1
      P1(I)=PN(I)
      P2(I)=PD(I)
      DO 590 J=1,N
      IF(I.EQ.J) GO TO 590
      PNN(I,J)=PNN(I,J)/SUM
      PND(I,J)=PND(I,J)/SUM
      PDN(I,J)=PDN(I,J)/SUM
      PDD(I,J)=PDD(I,J)/SUM
      IF(ABS(P1N(I,J)-PNN(I,J))/PNN(I,J).GT.A) IFLAG=1
      IF(ABS(P1D(I,J)-PND(I,J))/PND(I,J).GT.A) IFLAG=1
      IF(ABS(P2N(I,J)-PDN(I,J))/PDN(I,J).GT.A) IFLAG=1
      IF(ABS(P2D(I,J)-PDD(I,J))/PDD(I,J).GT.A) IFLAG=1
      P1N(I,J)=PNN(I,J)
      P2N(I,J)=PDN(I,J)
      P1D(I,J)=PND(I,J)
      P2D(I,J)=PDD(I,J)
      DO 580 K=1,N
      IF(I.EQ.K) GO TO 580
      IF(J.EQ.K) GO TO 580
      PNNN(I,J,K)=PNNN(I,J,K)/SUM
```

```
      PNND(I,J,K)=PNND(I,J,K)/SUM
      PNDN(I,J,K)=PNDN(I,J,K)/SUM
      PNDD(I,J,K)=PNDD(I,J,K)/SUM
      PDNN(I,J,K)=PDNN(I,J,K)/SUM
      PDND(I,J,K)=PDND(I,J,K)/SUM
      PDDN(I,J,K)=PDDN(I,J,K)/SUM
      PDDD(I,J,K)=PDDD(I,J,K)/SUM
      IF(ABS(P1NN(I,J,K)-PNNN(I,J,K))/PNNN(I,J,K).GT.A)  IFLAG=1
      IF(ABS(P1ND(I,J,K)-PNND(I,J,K))/PNND(I,J,K).GT.A)  IFLAG=1
      IF(ABS(P1DN(I,J,K)-PNDN(I,J,K))/PNDN(I,J,K).GT.A)  IFLAG=1
      IF(ABS(P1DD(I,J,K)-PNDD(I,J,K))/PNDD(I,J,K).GT.A)  IFLAG=1
      IF(ABS(P2NN(I,J,K)-PDNN(I,J,K))/PDNN(I,J,K).GT.A)  IFLAG=1
      IF(ABS(P2ND(I,J,K)-PDND(I,J,K))/PDND(I,J,K).GT.A)  IFLAG=1
      IF(ABS(P2DN(I,J,K)-PDDN(I,J,K))/PDDN(I,J,K).GT.A)  IFLAG=1
      IF(ABS(P2DD(I,J,K)-PDDD(I,J,K))/PDDD(I,J,K).GT.A)  IFLAG=1
      P1NN(I,J,K)=PNNN(I,J,K)
      P1ND(I,J,K)=PNND(I,J,K)
      P1DN(I,J,K)=PNDN(I,J,K)
      P1DD(I,J,K)=PNDD(I,J,K)
      P2NN(I,J,K)=PDNN(I,J,K)
      P2ND(I,J,K)=PDND(I,J,K)
      P2DN(I,J,K)=PDDN(I,J,K)
      P2DD(I,J,K)=PDDD(I,J,K)
  580 CONTINUE
  590 CONTINUE
  600 CONTINUE
      IF(IFLAG.EQ.1) GO TO 150
C
C     WRITE OUT VARIOUS PROBABILITY STATES
C     CALCULATION OF PROB(SYSTEM IS DOWN)
C
      IF(IWRITE.EQ.1) GO TO 609
      WRITE(6,900)A,KNTR,PO
  609 CONTINUE
      DO 610 I=1,N
      IF(I.LE.I1) ONEDN=ONEDN+PN(I)+PD(I)
      IF(I.GT.I1.AND.I.LE.I2) ONEDM=ONEDM+PN(I)+PD(I)
      IF(I.GT.I2.AND.I.LE.I3) ONEDO=ONEDO+PN(I)+PD(I)
      IF(I.GT.I3) ONEDP=ONEDP+PN(I)+PD(I)
      IF(IWRITE.EQ.1) GO TO 610
      WRITE(6,901)I,PN(I),I,PD(I)
  610 CONTINUE
      IF(IWRITE.EQ.1) GO TO 611
      WRITE(6,902)
  611 CONTINUE
      DO 618 I=1,N
      DO 615 J=1,N
      IF(I.EQ.J) GO TO 615
```

```
      IF(I.LE.I1.AND.J.LE.I1) DN=DN+PNN(I,J)+PDD(I,J)
     *+PND(I,J)+PDN(I,J)
      IF((I.GT.I1.AND.I.LE.I2).AND.(J.GT.I1.AND.J.LE.I2))
     *DM=DM+PNN(I,J)+PDD(I,J)+PND(I,J)+PDN(I,J)
      IF((I.GT.I2.AND.I.LE.I3).AND.(J.GT.I2.AND.J.LE.I3))
     *DO=DO+PNN(I,J)+PND(I,J)+PDN(I,J)+PDD(I,J)
      IF(IWRITE.EQ.1) GO TO 615
      WRITE(6,903)I,J,PNN(I,J),PND(I,J),PDN(I,J),PDD(I,J)
  615 CONTINUE
  618 CONTINUE
      IF(IWRITE.EQ.1) GO TO 619
      WRITE(6,904)
  619 CONTINUE
      DO 650 I=1,N
      DO 640 J=1,N
      IF(I.EQ.J) GO TO 640
      DO 630 K=1,N
      IF(I.EQ.K) GO TO 630
      IF(J.EQ.K) GO TO 630
      IF (IWRITE.EQ.1) GO TO 620
      WRITE(6,905)I,J,K,PNNN(I,J,K),PNND(I,J,K),PNDN(I,J,K),PNDD(I,J,K),
     *PDNN(I,J,K),PDND(I,J,K),PDDN(I,J,K),PDDD(I,J,K)
  620 CONTINUE
      IF(I.LE.I1.AND.J.LE.I1) GO TO 621
      IF(I.LE.I1.AND.K.LE.I1) GO TO 621
      IF(J.LE.I1.AND.K.LE.I1) GO TO 621
      IF((I.GT.I1.AND.I.LE.I2).AND.(J.GT.I1.AND.J.LE.I2)) GO TO 622
      IF((I.GT.I1.AND.I.LE.I2).AND.(K.GT.I1.AND.K.LE.I2)) GO TO 622
      IF((J.GT.I1.AND.J.LE.I2).AND.(K.GT.I1.AND.K.LE.I2)) GO TO 622
      IF((I.GT.I2.AND.I.LE.I3).AND.(J.GT.I2.AND.J.LE.I3)) GO TO 623
      IF((I.GT.I2.AND.I.LE.I3).AND.(K.GT.I2.AND.K.LE.I3)) GO TO 623
      IF((J.GT.I2.AND.J.LE.I3).AND.(K.GT.I2.AND.K.LE.I3)) GO TO 623
      IF((I.GT.I3).AND.(J.GT.I3).AND.(K.GT.I3)) GO TO 624
      GO TO 630
  621 DN=DN+PNNN(I,J,K)+PDDD(I,J,K)+PNND(I,J,K)+
     *PNDN(I,J,K)+PNDD(I,J,K)+PDNN(I,J,K)+PDND(I,J,K)+PDDN(I,J,K)
      GO TO 630
  622 DM=DM+PNNN(I,J,K)+PDDD(I,J,K)+PNND(I,J,K)+
     *PNDN(I,J,K)+PNDD(I,J,K)+PDNN(I,J,K)+PDND(I,J,K)+PDDN(I,J,K)
      GO TO 630
  623 DO=DO+PNNN(I,J,K)+PDDD(I,J,K)+PNND(I,J,K)+
     *PNDN(I,J,K)+PNDD(I,J,K)+PDNN(I,J,K)+PDND(I,J,K)+PDDN(I,J,K)
      GO TO 630
  624 DP=DP+PNNN(I,J,K)+PDDD(I,J,K)+PNND(I,J,K)+
     *PNDN(I,J,K)+PNDD(I,J,K)+PDNN(I,J,K)+PDND(I,J,K)+PDDN(I,J,K)
  630 CONTINUE
  640 CONTINUE
  650 CONTINUE
```

```
      DOWN1=ONEDN+ONEDM+ONEDO+ONEDP
      PSYSDN=DN+DM+DO+DP
      WRITE(6,906)PO,ONEDN,ONEDM,ONEDO,ONEDP,DOWN1,DN,DM,DO,DP,PSYSDN
  810 CONTINUE
  900 FORMAT(10X,'CONVERGENCE TO THE ',F9.6,' LEVEL REACHED IN ',I4,'
     *GAUSS-SEIDEL ITERATIONS',//,10X,'THE FOLLOWING PROBABILITIES ARE L
     *ISTED BY ORDER OF EQUIPMENT FAILURE',//,13X,'P(          0) = ',F10.
     *6)
  901 FORMAT(10X,'  PN(        ',I3,') = ',F10.6,10X,'  PD(        ',I3,') =
     * ',F10.6)
  902 FORMAT ( /12X,'I   J',7X,'PNN(I,J)',7X,'PND(I,J)',7X'PDN(I,J)',
     *7X,'PDD(I,J)',//)
  903 FORMAT(10X,2I3,4(5X,F10.6))
  904 FORMAT( //3X,'I   J   K',4X,'PNNN(I,J,K)',4X,'PNND(I,J,K)',4X,
     *'PNDN(I,J,K)',4X,'PNDD(I,J,K)',4X,'PDNN(I,J,K)',4X,
     *'PDND(I,J,K)',4X,'PDDN(I,J,K)',4X,'PDDD(I,J,K)',//)
  905 FORMAT(1X,3I3,8(5X,F10.6))
  906 FORMAT(10X,//,10X,'PROBABILITY OF ZERO DOWN = ',F10.6,/
     *10X,'PROB OF ONE TYPE 1 DOWN  = ',F10.6,/
     *10X,'PROB OF ONE TYPE 2 DOWN  = ',F10.6,/
     *10X,'PROB OF ONE TYPE 3 DOWN  = ',F10.6,/
     *10X,'PROB OF ONE TYPE 4 DOWN  = ',F10.6,/
     *10X,'PROBABILITY OF ONE DOWN  = ',F10.6,/
     *10X,'PROB OF AT LEAST TWO TYPE 1 DOWN  = ',F10.6,/
     *10X,'PROB OF AT LEAST TWO TYPE 2 DOWN  = ',F10.6,/
     *10X,'PROB OF AT LEAST TWO TYPE 3 DOWN  = ',F10.6,/
     *10X,'PROB OF AT LEAST THREE TYPE 4 DOWN  = ',F10.6,/
     *10X,'THE PROBABILITY THAT THE SYSTEM IS DOWN = ',F10.6,//)
  907 FORMAT(10X,F10.6,10X,F10.6)
  950 FORMAT(10X,' YOU DID NOT PROVIDE THE VALUE FOR  MEN  1,2,OR 3')
 1000 STOP
      END
```

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